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Submarine Canyon Wall Sedimentation and Lateral Infill: Some Ancient Examples

DANIEL JEAN STANLEY

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Submarine Canyon Wall
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Daniel Jean Stanley

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ABSTRACT

Stanley, Daniel Jean. Submarine Canyon Wall Sedimentation and Lateral Infill: Some Ancient Examples. *Smithsonian Contributions to the Marine Sciences*, number 4, 32 pages, 17 figures, 1980.—Submarine canyon wall and tributary sequences at three Annot Sandstone localities in the French Maritime Alps record early-stage resedimentation events in proximal sectors of the Tertiary Annot Basin. Canyon margin lithofacies are distinctive in that they comprise a more variable suite of stratal types than intracanyon slope, canyon axis, distal fan and basin series of the same formation. Characteristic criteria include the highly variable geometry and spatial distribution of the series of strata, irregular bedding thickness, paleocurrent directions that diverge from the predominant regional patterns, and discontinuities within the formation and between the Annot Sandstone and the older marine shale series (Eocene Marnes bleues) forming the canyon margins. Three distinctive sandstone stratification types dominate the "grès d'Annot" canyon wall association: type 1 units, moderately to well-stratified and massive (often amalgamated), emplaced by debris flow and a continuum of sediment-fluid flow mechanism, not specifically identifiable in the field; some thick sand layers may represent deposition as 'quick' beds from high-concentration underflows, possibly gradational between liquified and turbidity current flows; type 2 units, displaying slightly to extensive deformed horizons within but not throughout the beds, probably are related to liquefied flow and post-depositional liquefaction processes; and type 3 units, emplaced 'en masse' and in some cases showing complete disruption of primary stratification (chaotic bedding), are identified as slides and slumps. In addition to the three above types, lower proportions of graded, generally thin 'classic' sandstone turbidites (T_{a-b} , T_{b-c} , and T_{b-e}) and mudstone turbidites are recognized.

Although they appear as distinctly different entities in the field, a genetic relation between some depositional types is suggested. The mapped facies diversity is interpreted in terms of flow transformation, that is, the release of different sediment types along the dispersal path from a single sediment gravity flow as it evolves during its progression downslope. The diversity of mass flow products at the three canyon margin localities records a variable succession of transformation phases on the relatively steep slopes (locally in excess of 10°) within a short distance from the point of initial failure. The distinctive aspect of "grès d'Annot" canyon margin sedimentation is the repetitive erosion→transport→deposition pattern of lateral infill. Definition of these proximal lithofacies serves to better understand the origin of the more distal marine fan and Annot Basin plain sequences seaward of the three canyon localities examined and also can be applicable to the study of modern canyon-fan settings.

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Submarine Canyon Wall Sedimentation and Lateral Infill: Some Ancient Examples

Daniel Jean Stanley

Introduction

The importance of submarine channel systems in continental margin sedimentation is generally recognized, but modern canyon facies remain poorly defined and information on proximal canyon processes below SCUBA diving depths, more often than not, is based on inference rather than on actual observation. There are considerable logistical obstacles in obtaining sufficient data: the steepness and topographic complexity of canyon slopes, the narrowness of axes and the coarse, dense nature of canyon fill sequences have generally accounted for the poor resolution of echo-sounding and subbottom records, the uneven sample density, and the low penetration and inadequate recovery of cores in sand and gravel (Shepard and Dill, 1966). Consequently, the nature and origin of modern canyon wall deposits and their spatial and temporal relation to axial canyon facies remain poorly known. Moreover, little is known of processes involved during the early phases of down-slope transport when sediment fails, is displaced and then is redeposited on the steep canyon margin below canyon head depths. Workers have long realized that it is necessary to bridge this gap to attain a more precise understanding of sedimentation in deep environments at and beyond the base of continental slopes (Stetson and Smith, 1938; Bell, 1942; Shepard,

1951). Knowledge of processes in modern submarine canyons is based largely on direct observations in a rather limited number of modern settings, and on field investigations of possible ancient canyon analogs (recent reviews in Whitaker, 1976, and Stanley and Kelling, 1978).

This study focuses specifically on some ancient canyon wall deposits and attempts to provide further insight on sediment transport patterns in proximal channelized settings. Most ancient canyon investigations have described examples from the subsurface on the basis of core and seismic data (Almgren, 1978) and from surface sequences that are structurally deformed and, in most cases, only partially exposed (see examples in Whitaker, 1962; Carter and Lindqvist, 1975). A noteworthy exception is the well-exposed and structurally little deformed Tertiary Annot Sandstone ("grès d'Annot") Formation in the Maritime Alps of southern France (Figure 1). This sequence includes thick, massive sandstone belts, identified as submarine valley fills (Stanley, 1961), that merge with turbidite-rich sequences of intercanon slope, base-of-slope and submarine fan origin (Stanley, 1975). A number of "grès d'Annot" outcrops that comprise facies representative of different lower canyon and fan channel environments are distributed along major paleoslopes, and these exposures enable us to examine the sequential depositional patterns between steep proximal and the less steep, more distal, sectors of a continental margin and basin (paleogeographic scheme illustrated by Stanley, et al., 1978, Figs. 8-16).

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On the basis of this fortuitous distribution of good exposures several hypotheses have been elaborated in these earlier "grès d'Annot" studies. One pertains to the widely held tenet that submarine canyons are particularly suitable environments for the failure and displacement of sand-rich sediment by creep, slump, and various forms of gravity-induced mass flow including turbidity currents (Shepard and Dill, 1966). Such failure, in modern canyon heads, is largely attributed to the metastable physical properties of rapidly deposited sediment on relatively steep slopes (Moore, 1961; Dill, 1964). Abrupt loading associated with rapid deposition may be sufficient to initiate failure. Other commonly invoked triggering mechanisms of downslope failure are earthquakes (Chamberlain, 1964), movement of water masses (including storm, surge, tidal, and other current activity affecting the sea floor; cf. Keller and Shepard, 1978; Shepard and Marshall, 1978), and biogenic activity (Stanley, 1971; Rowe, et al., 1974; Warme, et al., 1978). Once set in motion, it is believed that gravity-driven sediment flows displace material of mud to gravel size along the length of canyons to fans and other distal base-of-slope environments, and observations in modern ocean basins tend to bear this out (Shepard, et al., 1969; Heezen and Hollister, 1971; Nelson and Kulm, 1973; Walker, 1978).

A second postulate to which attention also has been paid in recent "grès d'Annot" studies (Stanley, et al., 1978) proposes that once sediment fails and is set in motion on a submarine slope, the initial mass gravity mechanisms involved in the displacement of material can evolve to another type during the course of transport. This flow evolution during a single transport event is termed "transformation." For instance, it has long been implied that slumps transform to turbidity currents in canyons (Kuenen, 1951; Morgenstern, 1967). Recent investigations, based largely on theoretical considerations, but also on field observations, have outlined a rather more complex sequence of gravity-induced mechanisms that can occur between slumping and dilute turbidity current flow "end-members" processes (Dott, 1963; Middleton and Hampton, 1973; Carter, 1975; Lowe, 1976; Middleton and Southard, 1977).

This present study of "grès d'Annot" submarine canyon wall and canyon tributary deposits, an outgrowth of the previous investigations, is intended to identify the dominant most proximal sedimenta-

tion patterns. A survey of this type could provide further insight on the marked facies changes observed downslope in more distal settings. The examination of selected exposures should serve to (1) better define facies interpreted as canyon wall deposits, (2) document evidence of early-stage sediment failure in sequences believed to have moved along relatively steep slopes, and (3) identify the spectrum of mass gravity transport processes and their sequential evolution in the more proximal reaches of a continental margin.

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General Setting and Background Information

Briefly summarized here are the salient points that pertain to three outcrop localities where channelized sandstone tongues are exposed: Menton, on the Côte d'Azur Mediterranean coast, Contes, north of Nice, and the Braux region, east of Annot (Figure 1). The sand-rich units in the three regions were formerly termed, respectively, "grès de Menton", "grès de Contes" and "grès d'Annot". It is recognized that the base of these units is not strictly of the same age (ranges from Upper Eocene to Lower Oligocene, Campredon, 1972) and that they were deposited in different topographic depressions (Bouma, 1962). In a regional sense, however, the sandstone-rich units were deposited in the Nummulitic Sea, the final marine incursion in the region that occupied what is now the external sector of the southern Alpine Chain (Stanley, 1961), and are lithologically associated with, and genetically a part of, a regionally mappable series of marine sandstone and shale (with subordinate deposits of conglomerates) of approximately the same age. This entity is identified as a mappable formation that is now officially recorded as the "complex des grès d'Annot" (Bodelle, 1971; Campredon, 1972) and stratigraphically termed as such on the geological maps published by the French Bureau de Recherches Géologiques et Minières. Herein, the unit is abbreviated "grès d'Annot" or Sandstone.

Sedimentological investigations of the Annot Sandstone have been reported upon elsewhere, and the reader interested in overviews of the different "grès d'Annot" facies, regional basin paleocurrent and paleogeographic analyses and transport processes is directed to two recent syntheses (Stanley, 1975; Stanley, et al., 1978).

The exposures at the Menton, Contes, and Annot localities are comparable in the following respects:

1. Sandstone-rich sections form the upper member of a marine Paleogene trinity consisting, from the base up, of Middle Eocene limestone, including some conglomerates (conglomérats à nummulites), Upper Eocene blue shales and marls (Marnes bleues), and a sequence of Upper Eocene and Lower Oligocene sandstone and shale strata ("grès d'Annot").

2. The Annot Sandstone units occur in asymmetrically deformed synclines (generally the east limb of the syncline dips gently, about 30°, toward the west while the west limb dips steeply, and locally is vertical or overturned).

3. The original thickness of the "grès d'Annot" has not been preserved at the three localities since the top of this youngest marine formation is an erosional surface.

4. The most obvious sandstone exposures define linear SSE to NNW trending belts that consist largely of massive, moderately-well stratified, amalgamated pebbly-coarse sandstone strata identified as lower canyon to uppermost fan channel fills (Stanley, 1975; Stanley, et al., 1978).

5. These linear sandstone belts, ranging from 200 to over 300 m in thickness, are distributed in a direction that approximates the predominant paleocurrent directions (i.e., toward the north-northwest as simplified on the inset map in Figure 1).

6. This porportion of distinct turbidites, thin laminated sandstone units, and finer-grained layers, including shale, in the massive sandstone sections is low.

7. The contact between basal massive units of the thick shoestring sand bodies and the underlying Marnes bleues units is unconformable locally.

8. North-trending fingers of thick, massive sandstone beds are bounded to the east or west (or both) by thinner and much better stratified sequences including enhanced proportions of sandstone and mudstone turbidites; these series are identified as lower slope intercanion deposits (Stanley, 1975).

9. Annot Sandstone exposures north of the Annot, Contes, and Menton localities are much thicker (350 m to over 650 m preserved thickness), cover substantially greater surface areas, and comprise laterally extensive turbidite sandstone and mudstone sheets that alternate with channelized sandstone deposits; these are recognized as fan deposits (Stanley and Unrug, 1972; Stanley, 1975; Stanley, et al., 1978).

10. The paleocurrent indicators and mineralogical composition of these northern fan facies, as well as the exposures at Annot, Contes, and Menton, record a southern provenance and a principal north-trending dispersal pattern (Stanley, 1961; Bouma, 1962).

11. The fan deposits accumulated in the Annot Basin where depths locally exceeded 1000 m; bathyal depths are estimated on the basis of margin slope gradients conservatively estimated at approximately 3° to 5° (Stanley, 1961, 1975) and paleodepth evaluations of trace fossil assemblages (J. Wexler, unpublished data).

12. Paleogeographic reconstructions show that sand-rich series in the Menton, Contes, and Annot areas were deposited on margins that dipped northward, away from a large subaerially exposed region that occupied part of the present Ligurian Sea south of the Mediterranean coast (Kuenen, 1959; Stanley, 1961; Bouma, 1962; Bodelle, 1972).

Much attention has been paid to the thick, massive, relatively coarse-grained sandstone facies that comprise the bulk of the canyon and upper fan valley fills; some of these units have been interpreted as "quick" beds from high-concentration underflows (Stanley, et al., 1978). In marked contrast, the regionally more extensive Annot Sandstone facies to the north include much higher proportions of graded sandstone and texturally finer fractions. This turbidite-rich, typically flysch, facies has been interpreted as deposition from flows that bypassed the canyon mouths and released their load on fan lobes and in basinal areas.

Observations

Mapping indicates that the most distinctive attributes common to the sand bodies at Annot, Contes, and Menton are confinement and limited lateral migration, linear to gently sinuous 'shoestring' configuration, and a more southerly geographic position relative to the "grès d'Annot" base-of-slope and fan to basin series immediately to the north (Stanley,

1975). These sandstone bodies occupied important NNW-trending depressions, one to two kilometers wide, formed in the underlying Marnes bleues series.

Determination of the primary topographic configuration of the top of the Marnes bleues strata on which the "grès d'Annot" accumulated is essential to the discussions that follow. The original axial downslope inclination of the NNW-trending channelized pods is difficult to ascertain. However, the uppermost Marnes bleues surface mapped in an east-west direction normal to the "shoestring" sand axes reveal minimal primary slopes between the margins and axes that exceed 10° in the Contes area and in the Annot-Coulomp-Braux sector (summarized in Stanley, 1961, fig. 4 and Stanley and Unrug, 1972, figs. 26 and 28). The contact between the top of the Marnes bleues and the base of the overlying "grès d'Annot" sand pods define a V-shaped, relatively high-relief profile that is comparable with some modern canyons and uppermost fan valleys (Shepard and Dill, 1966). These geometric observations, coupled with the detailed lithofacies information (summarized in Stanley, et al., 1978), has led me to interpret the massive bedded "grès d'Annot" units at the three localities as deposits that accumulated near canyon mouths, near the base of north-dipping slopes.

The petrology and distribution patterns of the thick, usually amalgamated, sandstone bodies forming the canyon axis fill proper are detailed elsewhere (Stanley and Unrug, 1972; Stanley, 1975; Stanley, et al., 1978) and need not be described here. The facies bounding the valley axial fill, however, have not been sufficiently detailed, and attention herein is directed primarily to sandstone and shale deposits that draped the walls and filled lateral tributaries sculptured in the older Marnes bleues Formation. The arrows numbered 1 to 4 in Figure 1 show the location of the exposures illustrated in this study and their relation to the thick, linear SSE to NNW-trending canyon axes sandstone bodies. The field observations were made primarily: (a) near the village of Braux along road D110 that cuts the Crête de la Barre in the eastern part of the Annot syncline (arrow 1); along the lower parts of the cliffs formed by the massive sandstone west of the Coulomp River valley (arrow 2); (b) along road D115 near Sclos de Contes in the eastern part of the Contes syncline (arrow 3); and (c) along the series of the small roads (including D223 and D2566) that traverse the margins of the sandstone exposures in the Menton syncline (arrow 4).

The quality of exposures is very good to excellent at localities (a) and (b), but only moderate in the Menton area (c) due to the combination of vegetation and high concentration of dwellings that cover large surfaces of the weathered outcrops. The sandstone is moderately cemented and variably friable at the three localities, and the interbedded finer-grained units are compacted to shale and siltstone grade.

GENERAL ASPECTS AND GEOMETRY OF CANYON WALL FACIES

Canyon wall sequences are for the most part less than 100 m thick in contrast to the thicker (to 300 m) sandstone canyon axis fill units (compare Figures 2 and 3 with Figure 4); these are not true thicknesses, for in both cases the formation top is an erosional one. In contrast with the axial deposits, canyon wall facies include a much more diverse assemblage of stratal types and a significantly higher proportion of shale and fine-grained series interbedded with thick, massive sandstone units. Canyon wall facies comprising alternating sandstone and shale units, from a distance, appear flysch-like and resemble some base-of-slope fan and basinal deposits (Figure 2). On closer inspection, however, they are distinct from these more distal turbidite-rich sections as well as from adjacent intercanyon slope facies that consist of large proportions of thin, well-stratified, finer-grained laminated siltstone and sandstone units alternating with shales. The sand-shale ratio of some canyon wall sections approximates 1.0, in contrast to that of inter-canyon lower slope facies (about or less than 0.5; illustrated by Stanley, 1975, fig. 37), and of axial fill deposits (locally >32 at the Annot locality, Figure 4).

Even more obvious attributes of canyon wall facies are the highly irregular bed form, anomalous stratification attitude (Figure 4) and lateral discontinuity of the layers (Figure 2A). Marked thickness changes and wedging-out of bedding are commonly observed within a single exposure (Figure 2A, arrow *b*). Some beds can be traced for considerable distances, such as the 500m-long sandstone unit lying a few meters above the older Marnes bleues shales along road D115 at the Sclos de Contes locality; where examined in detail, however, thick strata such as these almost always are non-uniform internally and frequently display moderately deformed to "chaotic" internal stratification features (Figures 5, 6).

Some lenticular sandstone units may be sharp-based (Figure 7A, B) and show no significant erosion of the underlying layer. Others may truncate parts of the underlying unit (Figure 8), or erode thicker series of beds including the Marnes bleues shales that formed the underlying canyon walls (Figures 2A, 4B). The most extensive canyon wall units observed are the deformed and anomalously dipping massive sandstone units forming the lower portion of the cliffs bounding the west bank of the Coulomp River valley. Some of the anomalous bedding are actually surface weathering phenomena. In other cases, however, the attitude of thick strata clearly is at marked variance with the general strike and dip of the massive sandstone beds that overlie them (Figure 4); here, stratification planes record directions that are normal or even reversed to the predominant SSE to NNW dip of the linear sandstone belt (see fig. 22 in Stanley, 1975).

Maps of specific lithofacies reveal the marked discontinuity and lenticularity of strata along the length of the massive canyon fill shoestring bodies. This distinctive attribute of canyon wall deposits is illustrated by the patchy distribution of conglomerates, pebble-rich sandstone strata, and chaotic slump units on the margins of the canyon axial fill in the Contes area (Stanley and Unrug, 1972, fig. 28).

PREVAILING ASSEMBLAGE OF STRATA

A predominant characteristic of canyon wall deposits is the highly varied succession of sandstone stratal types (Figure 3). Three stratification types in particular form a substantial proportion (>50%) of the total thickness at some localities, such as the Crête de la Barre (Figures 3 and 7). None of these types is unique or specifically restricted to "grès d'Annot" canyon wall lithofacies; it is their relative importance and thickness that is characteristic. A brief description of each follows:

TYPE 1.—Well-stratified, massive, generally amalgamated sandstone units (Figure 7A) are present but in lower proportions and often thinner than in the associated canyon axis and more distal fan channel-upper fan sequences described by Stanley, et al. (1978). The strata consist of coarse sand or admixtures of coarse sand, granules, and small pebbles and range in thickness from 0.5 to about 10 m, but more commonly are 1 to 2 m thick. Some massive beds do not show any grading upward, while others are

moderately well graded (coarse-tail grading), particularly at the base of the bed. In graded beds the *a* Bouma division comprises the bulk of the bed, or this horizon may be topped by a moderately to well-defined *b* laminated sandstone division (Figure 8B). These T_a and T_{a-b} sequences often enclose isolated masses of deformed mudstone ("shale rip-up clasts") and sandstone blocks (Figure 9A, B) and armored mud balls (Figure 9C). These, and large cut-and-fill structures (Figures 8B) and discontinuous layers of shale (Figure 8A), record erosion by rapid succession of sand flows. Strata may be sharp-based (Figure 7A, B) or display sole markings (Figure 10), including tool (some to 30 cm in width) and scour structures, some of which may be load deformed. Convolute lamination (Figure 11A), and flame (Figure 11A), dish (Figure 11B) and related water escape structures are sometimes observed. Disturbance of bedding by benthic organisms (bioturbation) is low to moderate: animal burrows sometimes extend across an entire bed as much as 2 m thick (examples at the Crête de la Barre section), and grazing and trail markings often cover entire bedding surfaces (Figure 11C).

TYPE 2.—This is a particularly diagnostic type of stratification and one of the more common in terms of total number of beds in canyon wall sequences; in contrast, it comprises only a minor proportion of the adjacent canyon axis lithofacies. It is identified by the moderately to extensively deformed horizons within, but not throughout, the bed (Figures 7B, 12). Commonly, the basal 20 to 60 cm of a sandstone layer (which in some cases is graded) is undeformed; this layer is covered by a disrupted horizon of sandstone (Figure 12A) or a mix of sandstone and shale (Figure 12B, C). The disrupted or deformed to chaotic part of the bed, variable in thickness (usually 20 to 150 cm thick), may be covered by undeformed, structureless (Figure 12C) or horizontally laminated sandstone. A variant of this type includes sandstone strata that display deformed stratification at the base of, and not within, the bed (Figure 12D).

TYPE 3.—Strata of this type include sandstone, or shale, or sequences originally consisting of alternating sand and mud layers whose primary stratification has been completely disrupted (Figure 7C). These chaotic layers also occur in canyon axis-fan channel and base-of-slope environments, but in lower proportions. Several good examples of contorted layers (to 2 m thick)

are exposed at the Crête de la Barre (Figure 13A); the exposure at Sclos de Contes reveals thick (to about 10 m) chaotic mudstone-sandstone layers within massive sandstone (Figures 5, 13B). These spatially and temporally discontinuous sequences (Figure 6) are commonly identified as slump deposits. Anomalous stratified beds, such as those west of the Coulomp River valley (Figure 4) are also grouped in this assemblage.

OTHER TYPES.—The above three stratification types in the canyon wall sequences are complemented by variable, but generally low proportions, of thin (<50 cm) turbidites (T_{a-b} , T_{b-c} , or T_{b-e}), interbedded shale and shale-thin turbidite alternations (Figure 14), moderately to poorly stratified muddy, gravelly sandstones and gravelly sandstones (Figures 15, 16C), occasional layers of discontinuous sandstone flow rolls, and thin, well-defined layers of plant and mica incorporated in either sandstone or shale strata (Figure 11D). Most of the above types are much more important in the more distal facies to the north.

DISPERSAL PATTERNS

Sediment transport directions have been mapped on the basis of the measured orientation of sole marking and cut-and-fill structures, pebble orientation, and slump axes. More often than not, measured paleocurrent directions in the "grès d'Annot" canyon wall facies are not consistent either with prevailing trends (to the north) mapped in the adjacent lower slope intercanion series, or with the predominant current directions (SSE to NNW) of the major axial fill facies (Stanley, 1961; Stanley and Unrug, 1972; Stanley, 1975). Often scour or tool marks on a sandstone sole indicate several directions (Figure 10C), and this divergence may exceed 60° .

Noteworthy are the marked differences in current directions recorded within a single locality. For instance, at the Crête de la Barre, the direction of sole markings changes upsection from $S \rightarrow N$ and $SE \rightarrow NW$ to $E \rightarrow W$ and $NE \rightarrow SW$ (Figure 3). Some SW-trending flute marks at this exposure record dispersal almost opposite to the predominant NW paleocurrent direction recorded in the thick sequence of axial fill sandstone west of the Coulomp River less than 1 km distant. Sole marking directions recorded at Sclos de Contes, Menton, and the Crête de la Barre, which appear "anomalous" to the regional

trend, in fact indicate transport paths on slopes that are oblique or perpendicular to the major adjacent north-trending valley axes. Such paleocurrent measurements are actually consistent with a canyon wall and tributary canyon interpretation (Stanley, 1975) where terrigenous sediments likely would move on the steeper slopes and in tributary valleys oriented toward the canyon axis rather than down the more gently north-oriented continental margin.

TEXTURE, FABRIC, AND MICROSTRUCTURE

As might well be expected, the highly variable suite of stratal types interpreted as canyon wall deposits present a wide range of textures, fabric, and microstructures. A thin section and sieve analyses of over 110 samples collected at the three localities (this original unpublished data is available upon request from the author) sheds some light on the matter. Size frequency histograms for the friable, poorly cemented, massive sandstone samples show a bimodal distribution, i.e., a variable coarse modal class ranging from 0ϕ to 3ϕ , and a fine modal class in the finer than medium silt ($<5\phi$ range). The textural analysis shows that primary matrix content (herein defined as material finer than 31μ) ranges from about 3% to 30%, and is most commonly about 10% to 15% in the thick massive sandstones (Figures 15A, B). Canyon wall sandstone thus includes both mature and immature textural types, and is not substantially different in this respect than canyon axis deposits. Some canyon wall sandstone units, however, reveal a lower fine-grained fraction than sandstone turbidites that, to the north, dominate typical Annot fan and basin sequences (Stanley, 1961, 1975; Bouma, 1962).

The matrix content, usually a brown calcareous, silty mud paste, tends to be much higher ($>40\%$) in some chaotically deformed beds. As expected, grain-to-grain contact and matrix content generally show an inverse relation: the greater the amount of matrix, the lower the grain-to-grain contact, and vice-versa. A semi-quantitative estimate of packing was made by counting the number of grain contacts of sand-sized framework particles in 80 large thin sections. This two-dimensional analysis shows a frequency of contact ranging from about 4 to 7 contacts per grain in some of the lower matrix ($<10\%$) sandstone.

The maximum diameter of granules and pebbles of metamorphic, igneous, and sedimentary (excluding reworked shale and sandstone fragments) origin usually ranges from 0.5 to 3.0 cm. Coarse fraction fabric studies in the field provide complimentary information on dispersal patterns. Pebbles may be concentrated at the base of sandstone beds and show grading (Figure 8B) or reverse grading (Figure 16B), or they may be irregularly dispersed in sandstone or muddy sandstone units. An attempt has been made to compare pebble orientation with sole mark directions in the same bed. Pebbles in some units are imbricated with the elongate axis dipping upslope (Figure 16A, B), but as a general observation clasts in most strata display a more random orientation and imbrication (Figure 16C).

Large thin sections cut in sandy canyon wall deposits often show structures not visible on a weathered outcrop surface, such as vague or disrupted laminae, or the injection of finer textured siltstone in sandstone (Figure 15B). Laminae commonly consist of alternations of grain-thick layers of silt and sand, mica blades, and plant fragments. In some thin sections, laminae are deformed (Figure 15C) or discontinuous (pillars, convolutions, dish structures, Figure 11A, B), and these water escape features record late transport or early post-depositional mechanisms (Lowe, 1975). Bioturbation structures probably also modified the original fabric of some sandstone and siltstone layers.

Interpretation of Dominant Stratal Types

The assignment of specific transport mechanisms to "grès d'Annot" strata on the basis of observed stratification features should be approached with considerable caution. Several of the obvious sedimentary structures may be attributed to more than one emplacement mechanism. The depositional origin of other specific structures remains ambiguous. To complicate matters, it is likely that many of the sandstone types examined were emplaced by gradational, not pure "end-member" gravity flow mechanisms (Middleton and Hampton, 1973, 1976; Lowe, 1976a, b). Moreover, structures and fabric tend to record terminal, or "freezing," depositional events (Walton, 1967; Carter, 1975) and post-depositional, including liquefaction, phenomena (Lowe, 1975) rather than active transport and immediately pre-

depositional stages. In spite of these limitations, field description, coupled with laboratory petrologic examination, still provide the most useful data base with which to initiate a discussion of downslope transport processes in the environment under consideration. In so doing here, it is recognized that reasoning is largely by analogy, i.e., evaluating the final preserved product in light of theoretical and experimental investigations and by comparison, where possible, with analogs in modern subaqueous settings.

The "grès d'Annot" sandstone strata described earlier all record some form of resedimentation involving failure and flow of sediment accompanied by a disruption of the original grain framework and formation of a new suite of primary structures upon deposition. Grain framework changes on the one hand induced failure, and also developed as a result of failure and downslope displacement. Attention is first directed to the type 3 stratification units that are particularly distinctive and which group "en masse" emplaced and chaotically stratified sediment sequences; these, widely recognized in both the modern and ancient sediment record, include slides and slumps. These are distinguished from the deposits of sediment gravity flows (flowage of sediment-fluid mixtures), and the presence of a gradient is needed for extensive displacement of both depositional types. Among the more striking examples of slides are thick, anomalously dipping strata that form the lower part of the Annot Sandstone cliff section west of the Coulomp River valley in the Annot area (Figure 4). It is herein suggested that large, partially consolidated sandy slabs moved along a well-defined set of slippage planes and were emplaced downslope "en masse" toward the base of the canyon margin. The mapped stratification attitude indicated preferential transport toward the west, that is, primarily toward the channel axis (dispersal depicted by Stanley, 1975, fig. 22B). Sliding on a somewhat more moderate scale is also denoted by the locally deformed base of the massive sandstone unit at the Sclos de Contes locality (Figure 12D).

Slumping, involving displacement along multiple slippage planes, has resulted in movement of somewhat smaller masses of sediment. Shear during movement deformed most original structure and fabric, although some can generally still be recognized; the deposits suggest a churning motion that mixed unconsolidated mud and sand. Good examples of chaotic

structure include the large shale and sandstone masses incorporated in the massive bedded unit at Sclos de Contes (Figures 5, 6, 13B), and several highly deformed layers of variable thickness at the Crête de la Barre section near Annot (Figure 13B).

Somewhat less obvious in the "grès d'Annot" exposures than slides and slumps but more significant in terms of number are sandstone layers with pronounced deformation within the bed and/or at the bed boundaries. These, earlier described as type 2 stratification units, are the product of several sediment flow processes, including liquefied flow on the basis of criteria described and illustrated by Lowe (1976b). A remarkable variety of such beds are exposed at the Crête de la Barre section (Figures 7B, 12A-C). These display slight to extensive disruption of stratification, recording a collapse of metastable, loosely packed sand. Collapse, according to Lowe (1976b) and others, can occur just before failure by spontaneous liquefaction (cf. Terzaghi, 1956), or as a result of liquefaction following failure. Dilation and fabric breakdown under increased stress in some instances may have been induced along horizons of originally increased porosity and water content. Such horizons may have included laminations of mud, mica, and plant matter mixed with sand- and granule-size material as observed in field and thin-section observations (Figure 11D). Water squeezed out of loaded underlying sediment also may have triggered liquefaction in beds emplaced by sediment flow mechanisms other than liquefied flows. Experimental work suggests that as grains temporarily lose contact, flowage occurs on slopes of 10° or less for short distances before resedimentation. The process can begin by slump-creep (Carter, 1975) and retrogressive flow slides (Lowe, 1976b) and also can involve the "rafting" of sand above the failed zone. Probably internal deformation also records late-stage post-depositional liquefaction (Lowe, 1975). Similar modern deep marine analogs include the muddy organic-rich fills in some steep-walled canyon heads that fail by processes of creep and semi-continuous sand slumps as described by Dill (1964, 1967), Chamberlain (1964), and Marshall (1978).

Stratification types 2 and 3 are probably most diagnostic of "grès d'Annot" canyon wall facies, but the exposures in the three study areas also include a large proportion of massive sandstone beds grouped as type 1 units. Descriptively these moderately to

well-stratified beds can be readily distinguished from the more typical slide, slump, and internally deformed sandstone layers; in terms of emplacement, however, they are probably related to these processes. As a group, type 1 units display structures attributed to a spectrum of sediment-fluid flow processes that, depending on the author, would include grain flows (Stauffer, 1967), fluidized (Middleton and Hampton, 1973) and liquefied (Lowe, 1976b) flows, slurry flows (Carter, 1975), and "quick" beds from high-concentration underflows (Middleton, 1967; Stanley, et al., 1978) and, in the case of muddy, pebbly sandstones, to debris flows (Hampton, 1972). Some studies, for instance, have suggested that fluidized flows (sediment is supported by the upward flow of fluid escaping between grains) and grain flows (sediment is supported by grain-to-grain interactions, cf. dispersive pressure of Bagnold, 1956) could not account for the formation of the thick sandstone units encountered in ancient deep marine sequences (Lowe, 1976a, b). At this time there remain fundamental disagreements as to the physics of particle-fluid motion, natural conditions required, and specific structures of resedimented, thick, non-graded sandstone layers. A classification of sediment gravity flows that emphasizes grain support mechanisms (by fluidization, grain-to-grain interaction, fluid turbulence, and matrix strength) presented by Middleton and Hampton (1973) is appealing because it takes into account a possible gradation between such grain support mechanisms during flow. In most cases, however, it would be premature to attribute sedimentary structures of a "grès d'Annot" type 1 coarse, massive bedded sandstone to a specific grain support mechanism. Fabric, an attribute most affected by final stage and post-depositional events, is of questionable value in making such an assessment. Matrix content, however, may be a more reliable indicator of process. Thin-section and sieve analyses show that matrix content in type 1 units ranges from less than 5% to over 30% (Figure 15A), and this silt and clay material, once part of the interstitial fluid, aided in suspension of the larger grains during flow (Hampton, 1972).

For field work purposes, a very simplified genetic subdivision of type 1 sandstone beds involves two very generalized process "end-members": (a) flowage of sediment-fluid mixtures involving matrix strength where larger grains have been supported by

a mixture of fluid and fine sediment; such deposits, attributed to debris flow, usually display coarse grains "floating" among finer grains, but no graded bedding, and generally contain a substantial matrix content (Figure 16); and (b) water saturated flow involving lower matrix strength, somewhat lower clast concentrations and gradational spectrum of grain support mechanisms (grouping liquified, fluidized, grain, slurry, and dense turbidity current flows of the various authors cited earlier), and non-specifically termed "sand flow" (Stanley, 1975). The latter is applied until more precise criteria are developed for interpreting thick sandstone deposits with or without sole markings that display no or poorly developed graded bedding (Figure 7A) or, occasionally, reversed graded bedding and water escape structures. Indication of the turbulent nature of the base of such flows is recorded by the multiple sole marking orientation (Figure 10C); rapid deposition of the highly charged mass resulted in final stage and post-depositional rearrangement of sediment grains by escaping water (see structures in Figures 11A, B and 15 A, C). Some Type 1 massive sandstone sand flow deposits that display poorly to moderately developed graded bedding (Figure 14B) and an incomplete sequence of Bouma (1962) divisions were probably emplaced by a continuum of high density flows that involve turbulence and dispersive pressure as grain support mechanisms. These strata are identified as T_a and T_{a-b} turbidites (Figure 14A) deposited from high-concentration underflows (cf. Middleton, 1967) or from flows transitional between liquefied and turbidity currents (Lowe, 1976b).

In addition to stratal types 1, 2, and 3, there are sandstone units that account for a lower proportion of the total "grès d'Annot" canyon wall lithofacies, but whose origins are somewhat better understood. These include thinner "classic" graded T_{a-c} , T_{b-c} , and T_{b-e} turbidites (Figure 14C) at each of three canyon localities. Turbidity currents also were responsible for the emplacement of a significant proportion of thin laminated silt and shale layers at the Crête de la Barre (Figure 14C). Thin-section, grain size, and compositional studies indicate that muddy turbidity flows (criteria based on those defined by Rupke and Stanley, 1974, and Piper, 1978) were more important than hemipelagic suspension processes in the deposition of interbedded shales in the study areas.

Lateral Infill: Inferences and Discussion

The highly varied assemblages of Annot Sandstone stratal types, their aerially restricted distribution along margins of channelized sand bodies, and the interpreted transport processes collectively define a distinctive resedimentation pattern. The geometric, petrologic, and paleocurrent attributes at the Menton, Contes, and Annot localities record the deposition of coarse-grained terrigenous materials in restricted slope environments where transport trends are oriented largely toward channelized "shoestring" sandstone bodies. Together, observations and speculations help elucidate lateral infill phenomena on lower canyon flanks, probably at a position close to the mouth of the canyons.

The original thickness of the Annot Sandstone is not preserved (the top of the Formation is an erosional surface), but overall it appears that deposits interpreted as canyon wall and tributary sequences are thinner and considerably more irregular in geometry and temporal-spatial distribution than the associated canyon axes facies. Most individual layers cannot be correlated over distances in excess of one kilometer. Also obvious are the unconformities between the Annot Sandstone and underlying Marnes bleues shales, and within the Annot Sandstone, suggesting that the canyon margins were unevenly covered by sand, muddy sand, pebbly sand, pebbly mud, and silty mud. Although individual layers are spatially restricted, the considerable thickness of many "grès d'Annot" beds (commonly ranges from 0.5 to 4.0 meters) indicates displacement of large volumes of material by single sediment transport events. This becomes apparent if one considers that a lenticular 1-meter-thick sand unit deposited over a 1 km² surface involves downslope transport of at least one million cubic meters of sediment. Periodic failure of packets of sand and mud would have exposed, at least locally, the Marnes bleues shales that formed the underlying canyon margin surfaces (schematic profile in Figure 17).

The diverse successions of slides, slumps, and products of debris flow and various sand flow mechanisms characterize dynamic reworking (recurring failure→erosion→transport) rather than a progradational regime (transport→deposition→permanent emplacement). It is expected that a regime of this type, where erosion and mass wasting of the canyon margins prevailed, would have contributed some of

the material that could be moved downslope. Sliding and slumping were particularly important in fostering this intrabasinal provenance-and-dispersal phenomenon. The slower sawing and grinding action of sand against stiff, partially lithified series forming the margins also may have been an effective process; undercutting by moving sand leads to failure as has been shown in modern canyon heads (Dill, 1964). Some indication of erosion by sand is recorded in "grès d'Annot" exposures by cut-and-fill (Figure 8B) and small channel structures (Figure 16C), and by the partial to complete removal of mud and thin sand layers between and within the thicker, massive sand layers (Figure 8A). The burrowing action of organisms also contributed to the weakening of partially consolidated "grès d'Annot" and Marnes bleues series forming the canyon wall and tributary surfaces (Stanley, 1971). Failed undercut and bioturbated sections provided mud and sand fragments of varying size and shape commonly observed as shale and sandstone clasts in the thick, massive-bedded sandstone units. These olistoliths, some quite large (>1 m), were initially "rafted" on the slowly moving mass of sand, while others subsequently were remobilized and incorporated in the sandy units emplaced further downslope by debris and high-density flows, including turbidity currents. Armored mud balls (Figure 9C) show that the eroded blocks of mud were subjected to rounding and became coated with sand and granules during the short down-margin transit toward the axis.

From the study of canyon heads off Southern California (Chamberlain, 1964; Shepard and Dill, 1966) and in the Mediterranean (Groupe Estocade, 1977) and theoretical and experimental investigations of resedimented deposits it is surmised that failure and initiation of flow in the Annot Sandstone environment under discussion can be triggered by diverse mechanisms. These, summarized from Lowe (1976b), include: earthquakes; abrupt loading associated with rapid deposition; development of excess pore-fluid pressures through movement of artesian water; failure of sediment accumulated to a slope near its internal friction angle; failure by loss of support by sediment undercutting sediment sections; failure along planes of weaknesses (underconsolidated mud laminae; bioturbated horizons (Stanley, 1971); plant, mica, and organic-rich layers, etc.). Recent work shows that the vibratory action of water masses

concentrated in canyons, as discussed by Shepard and Marshall (1978), also is a potential trigger mechanism. The specific cause of slides, slumps, and gravity sediment flows in the Annot Basin remains undefined, but a combination of several factors is suspected: the entire formation accumulated in two million years or less (Stanley, 1961) implying a rapid build-up of sediment and loading on the outermost shelf, uppermost slope and canyon margins; and earthquake tremors also would have been likely in this rapidly evolving structural setting at the end of the Eocene and early Oligocene. Rapid deposition of sand on tectonically mobile subaqueous slopes would provide conditions suitable for the inducement of sudden changes in physical properties (framework grain support, porosity, reduction of internal resistance to shear); it would, in fact, be difficult to envision permanent accumulation of the prograding sand-rich masses under such conditions.

The "grès d'Annot" canyon margin processes are identified with different degrees of confidence. The deposits emplaced by slumping, debris flows, and turbidity currents are more readily recognized. As was earlier emphasized, however, most sandstone layers were transported by less obvious gradational flow mechanisms involving debris flow, liquefied flow, and high-concentration flows, including turbidity currents. It is likely that the quick massive stratal types were released from mass flow transport events that evolved during their progression downslope, and a lateral infill scheme is envisioned whereby slumps and retrogressive flow slides transformed to debris and sand flows and even dilute turbidity currents within the small distance and short transit time involved. The lithofacies succession indicates a distinctive repetitive pattern of erosion→transport→deposition. Some hypothetical examples are depicted in Figure 17: diagrams A to C illustrate simpler modes, and D to F show more complicated possibilities. In A the sediment mass is displaced by creep and creep-slump processes and then further modified by liquefaction; this is recorded by some type 2 stratification units (Figure 12). B depicts transport evolving to slumps or slides, resulting in type 3 units (Figure 13). In C creep, slump-creep, and retrogressive flow slides give rise to fluid-sediment flows involving debris and a variety of high-concentration sand flows, including turbidity currents; the deposits as a group are identified in the field as type 1 units. Modes D, E, and F

show somewhat more complex failure→transport→deposition patterns. It is this variable succession of transformation events that is the most distinctive aspect of Annot Sandstone canyon margin sedimentation.

The lateral infill regime outlined above affected sedimentation in adjoining parts of the Annot Basin margins. For example, movement of substantial volumes of material from the canyon walls to the axis probably triggered movement upslope in the canyon as well as downslope in the canyon axes by a "chain-reaction" effect as has been proposed for some modern canyons (Stanley, 1974). Also worth noting is the presence at Menton, Contes, and Annot of thick T_a and T_{a-b} sandstone layers of probable turbidite origin and minor proportions of more complete turbidites in both the canyon margin and canyon fill facies: turbidity currents initiated up-canyon released an important part of their coarse fraction load in geographically proximal sectors prior to and upon reaching the canyon axis. This would

substantiate the contention that transformations from slumping, liquefied flows, and other sediment gravity flows to turbidity currents (where grain support is primarily by fluid turbulence mechanisms) occurred primarily on the steeper slopes of the canyons and uppermost fan sectors seaward of canyon mouths as suggested in an earlier study (Stanley, et al., 1978). As presently envisioned, coarse materials from turbidity current related high-concentration underflows were trapped on the margins and in the axes of lower canyons and fan channels, while thinner sheets of better developed graded sandstone and finer fractions forming large fan lobes in the Annot Basin were released progressively from the more dilute parts of these turbidity currents.

Detailed analyses of sediment gravity flows and their deposits in different modern canyon settings are needed to amplify knowledge on lateral infill patterns and to further test some of the ideas proposed in the present investigation.

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Figures

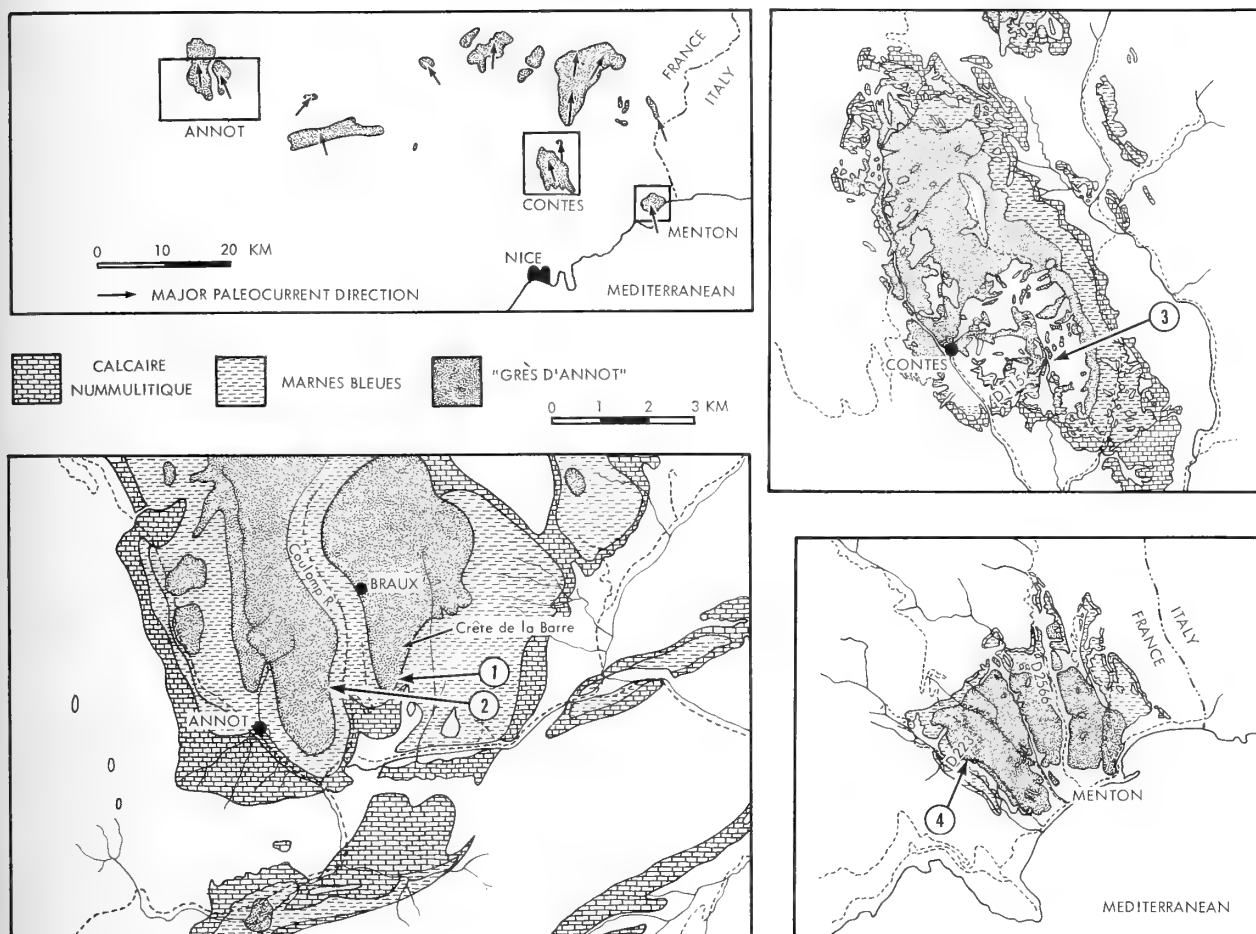


FIGURE 1.—Maps showing location of Annot Sandstone in three synclines in French Maritime Alps; formation overlies Eocene shale (Marnes bleues) and limestone (calcaire nummulitique) series. (Arrows = position of canyon margin exposures discussed in text: 1, Crête de la Barre section; 2, base of cliffs west of Coulomp River valley; 3, Sclos de Contes section; and 4, exposures along road D-223 northwest of Menton.)

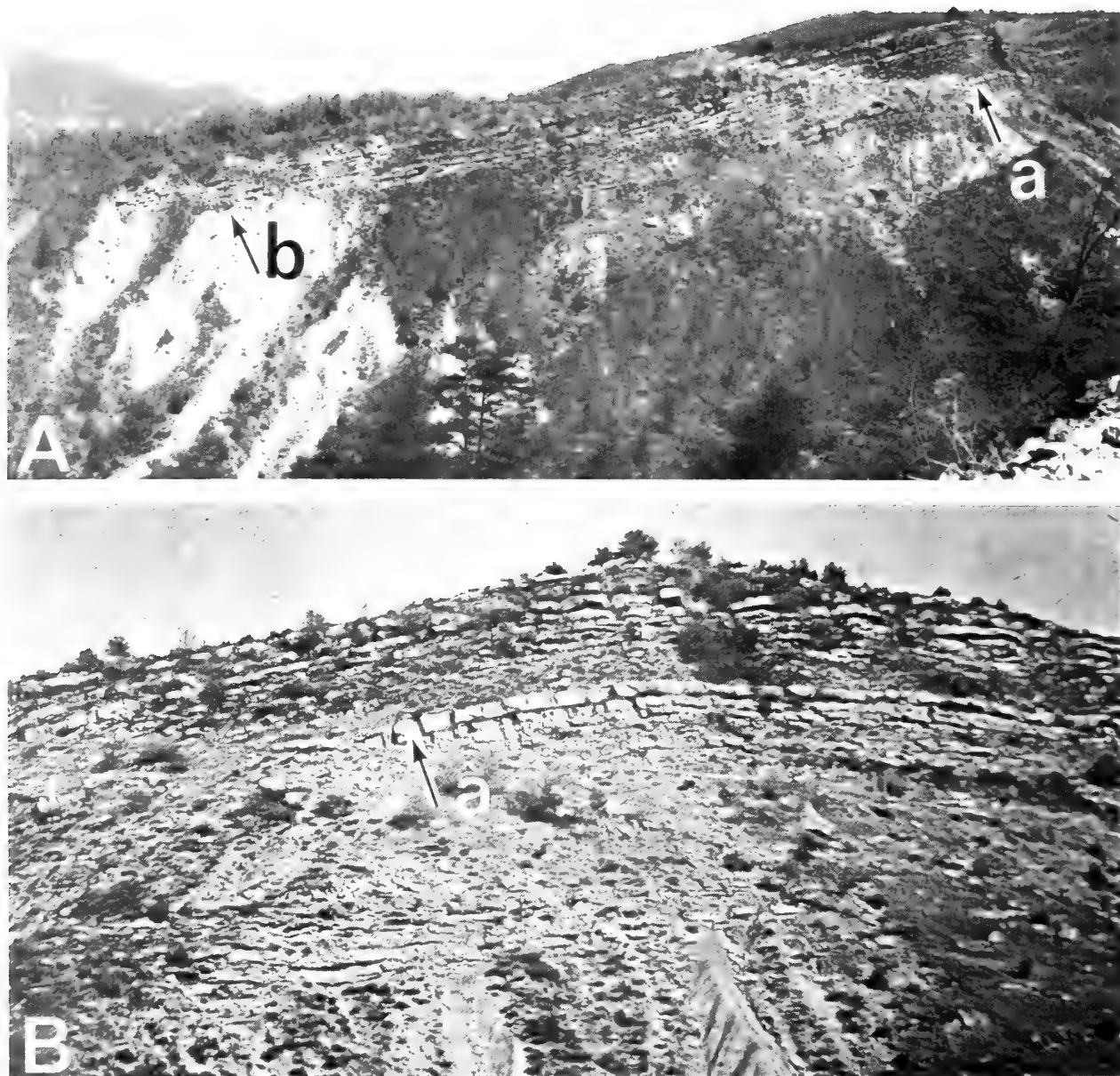


FIGURE 2.—Photographs oriented toward northwest showing Crête de la Barre section in Annot syncline (Figure 1, arrow 1). (Arrow *a* = stratal thickness changes along outcrop; arrow *b* = pinch-out and unconformable contact of "grès d'Annot" section with underlying Marnes bleues shales that formed lower canyon margin.)

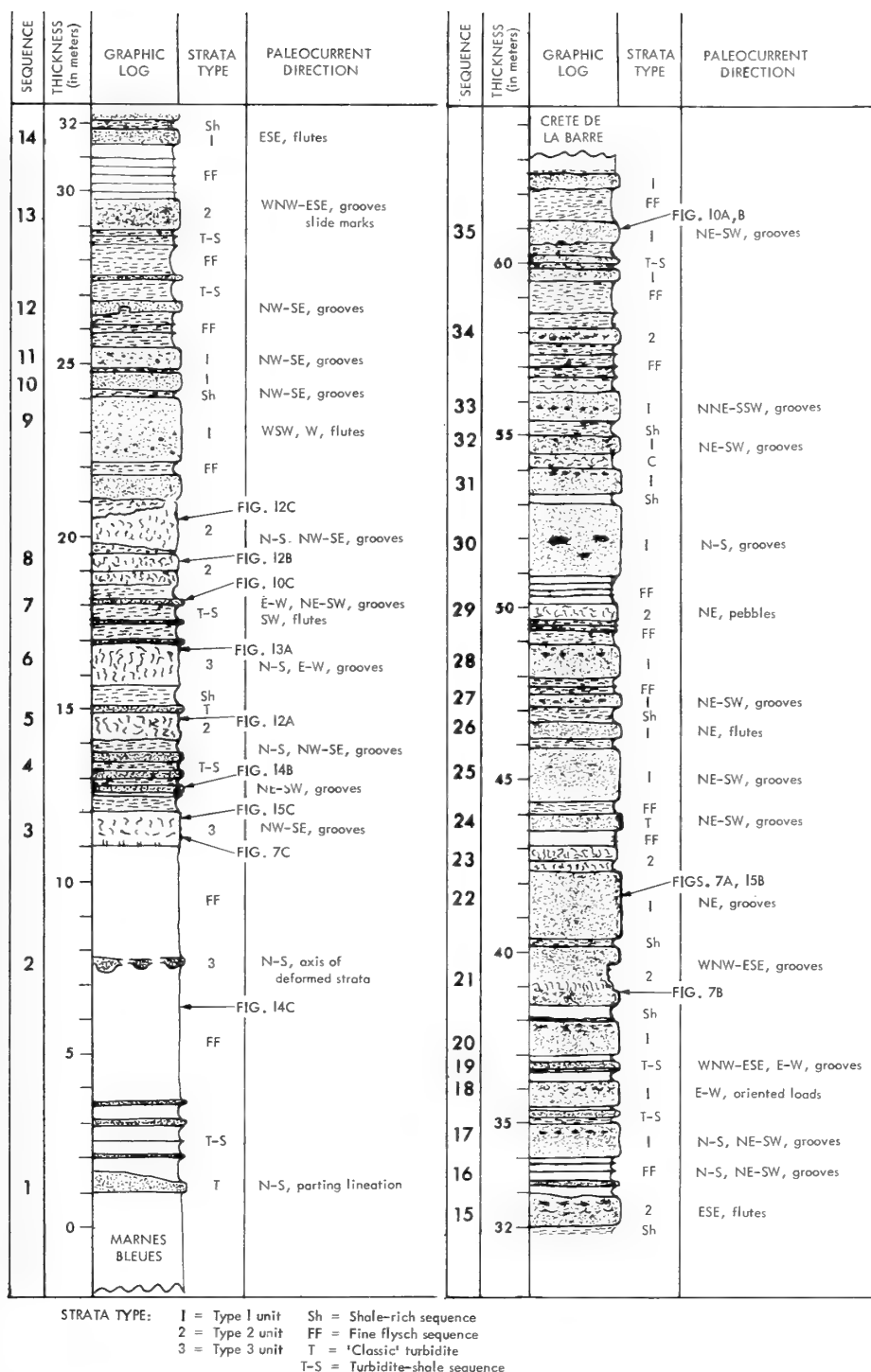


FIGURE 3.—Simplified graphic log depicting facies at Crête de la Barre section near Braux interpreted as tributary canyon deposit (modified from Stanley, 1975). (Note lithologic, paleo-current, and stratification diversity; different strata types are described in text and photographs of specific examples, denoted by arrows, are illustrated in Figures 7 to 16.)

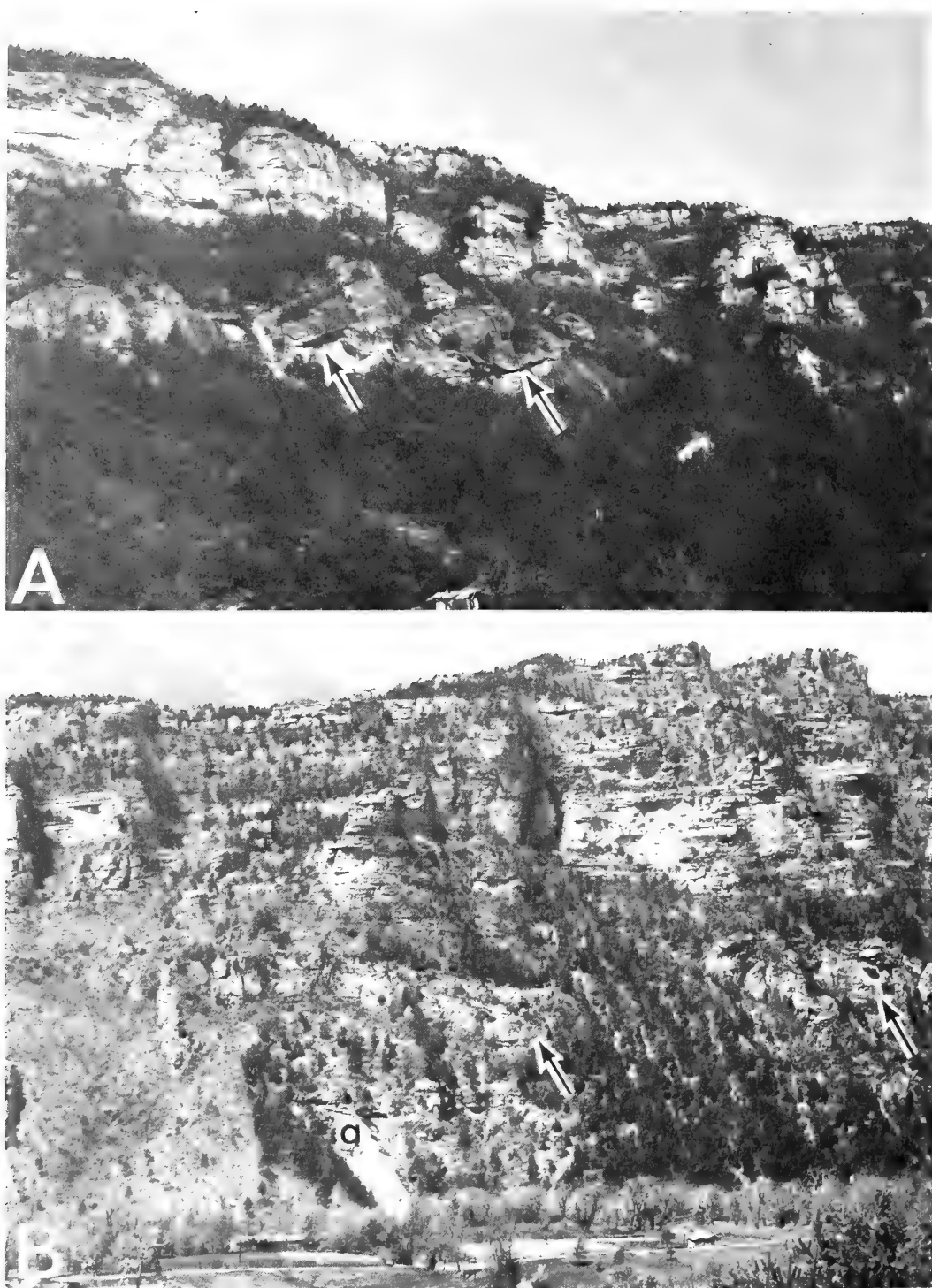


FIGURE 4.—Annot Sandstone exposures west of Coulomp River valley (Figure 1, arrow 2), showing anomalously dipping stratification of slide deposits that form lower part of section (arrows); base of “grès d’Annot” section at *a* truncates underlying Marnes bleues shales.

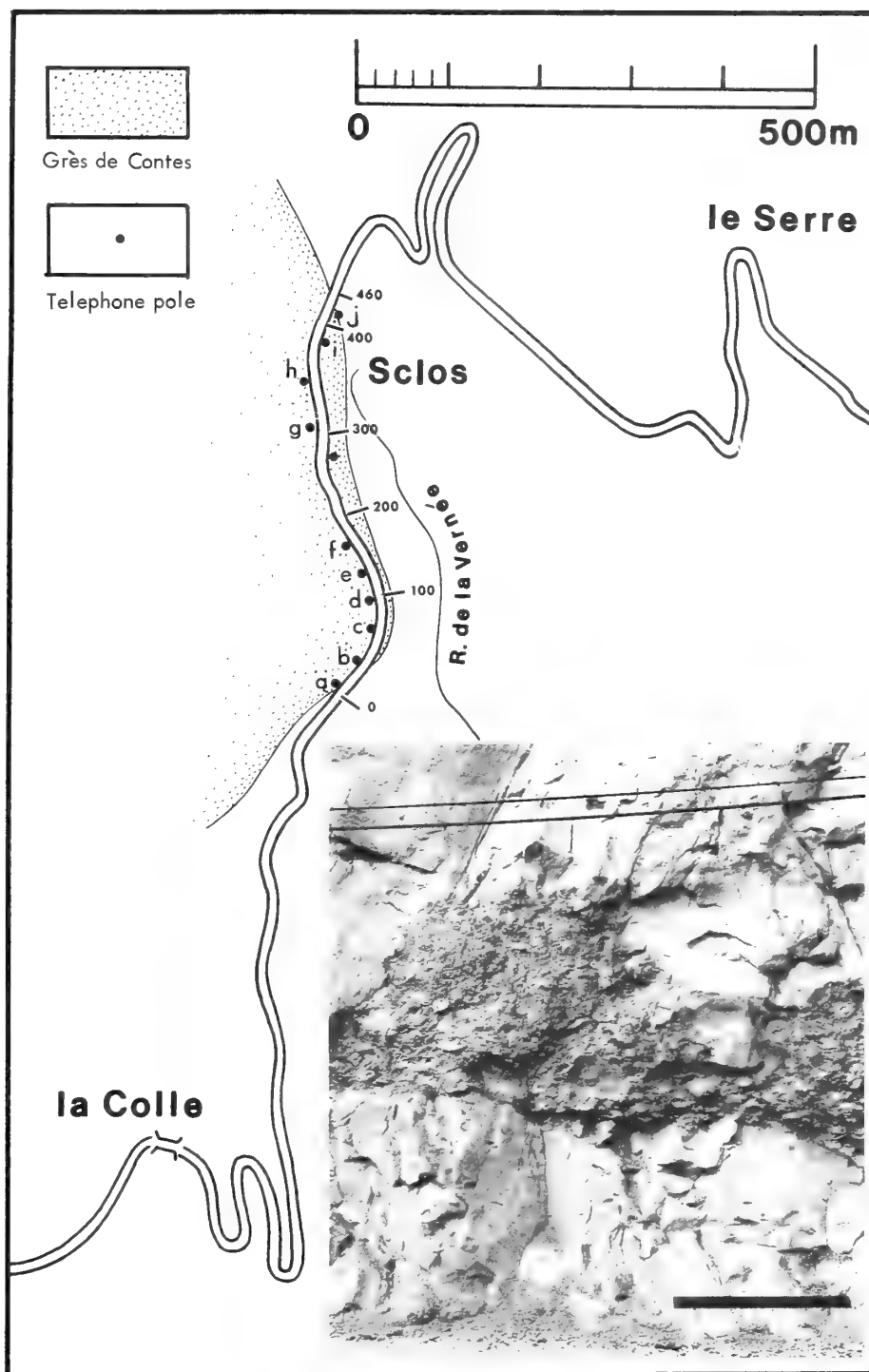


FIGURE 5.—Detailed map of Annot Sandstone at Sclos de Contes (road D-115) locality in the Contes syncline (Figure 1, arrow 3). The 500 meter-long road-cut section is illustrated in Figure 6; photo inset illustrates a slump unit of contorted sandstone and shale within the massive sandstone (bar = 150 cm).

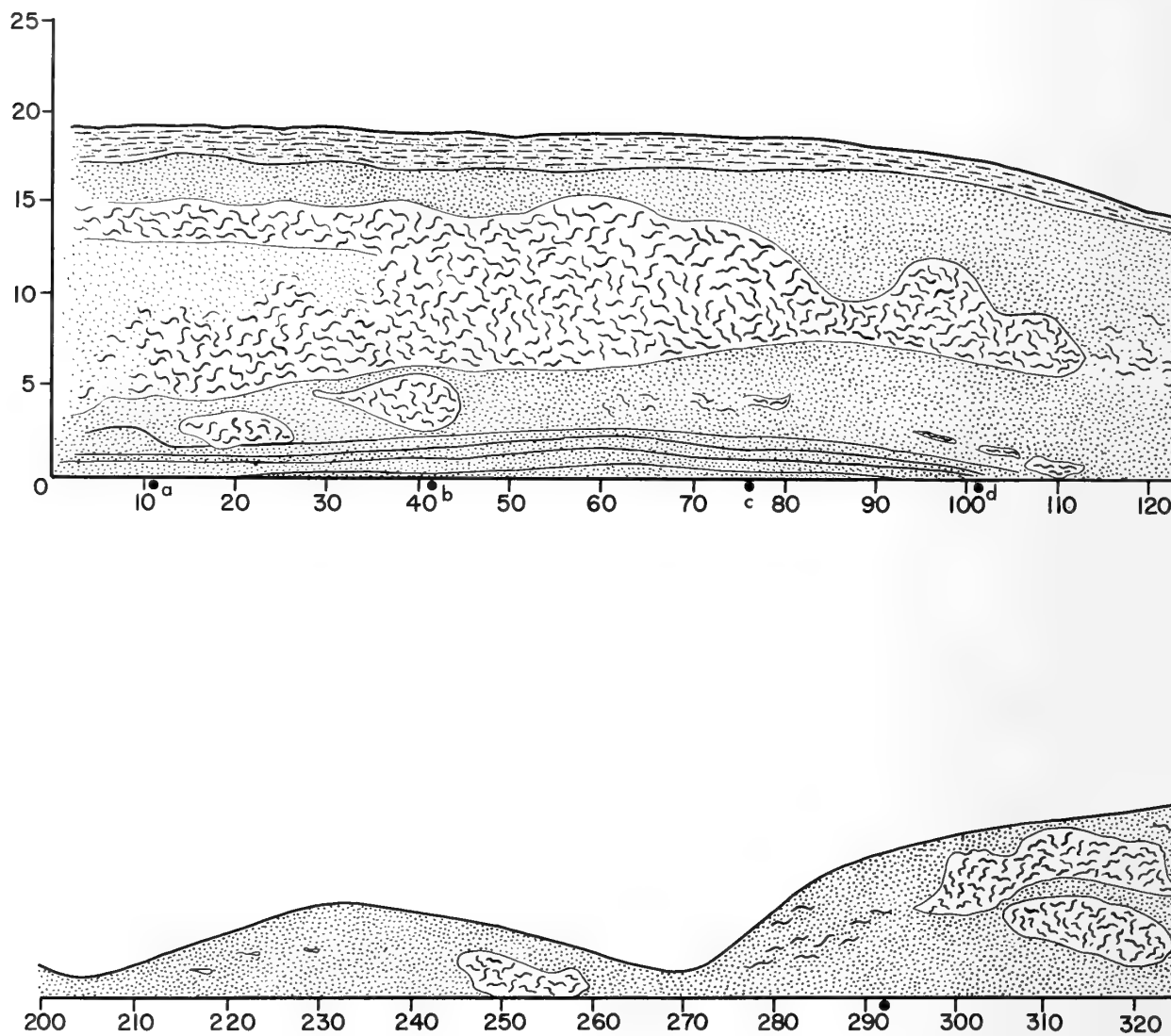
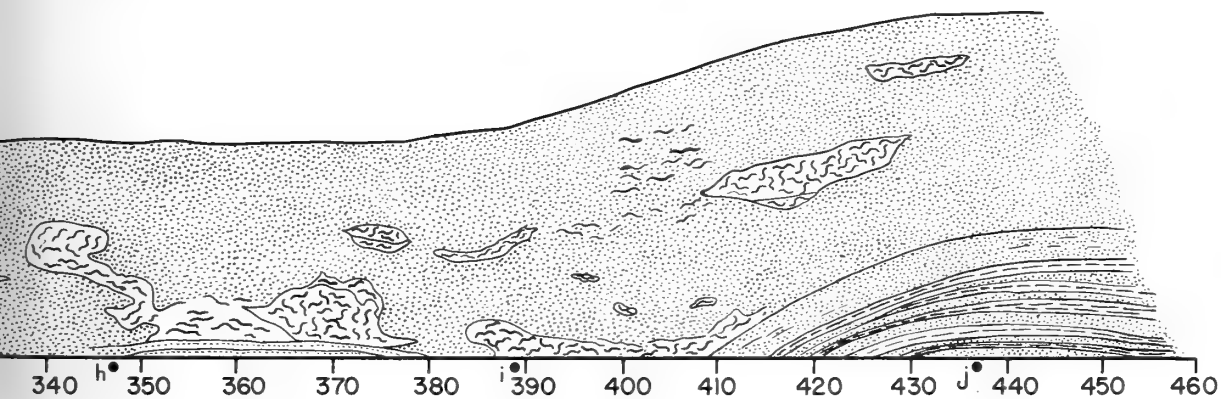
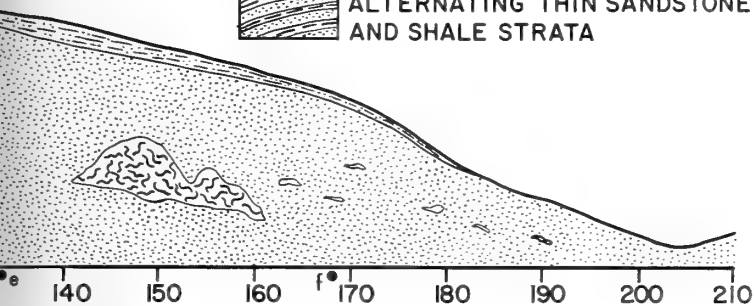
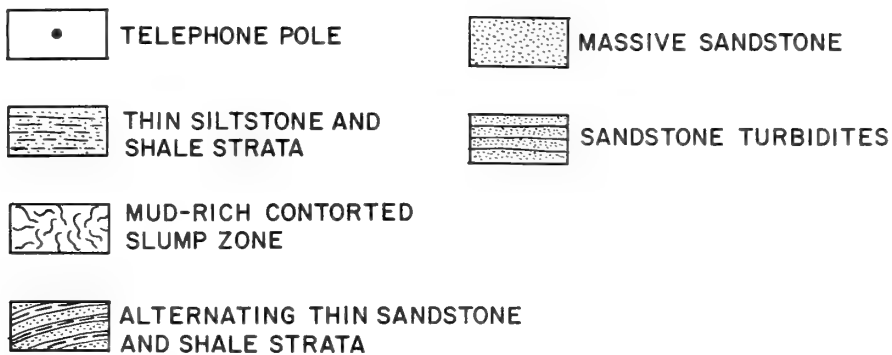


FIGURE 6.—Graphic depiction of Annot Sandstone exposure at Sclos de Contes locality (Figure 5). (Horizontal and vertical scales in meters; $\times 2$ vertical exaggeration.)



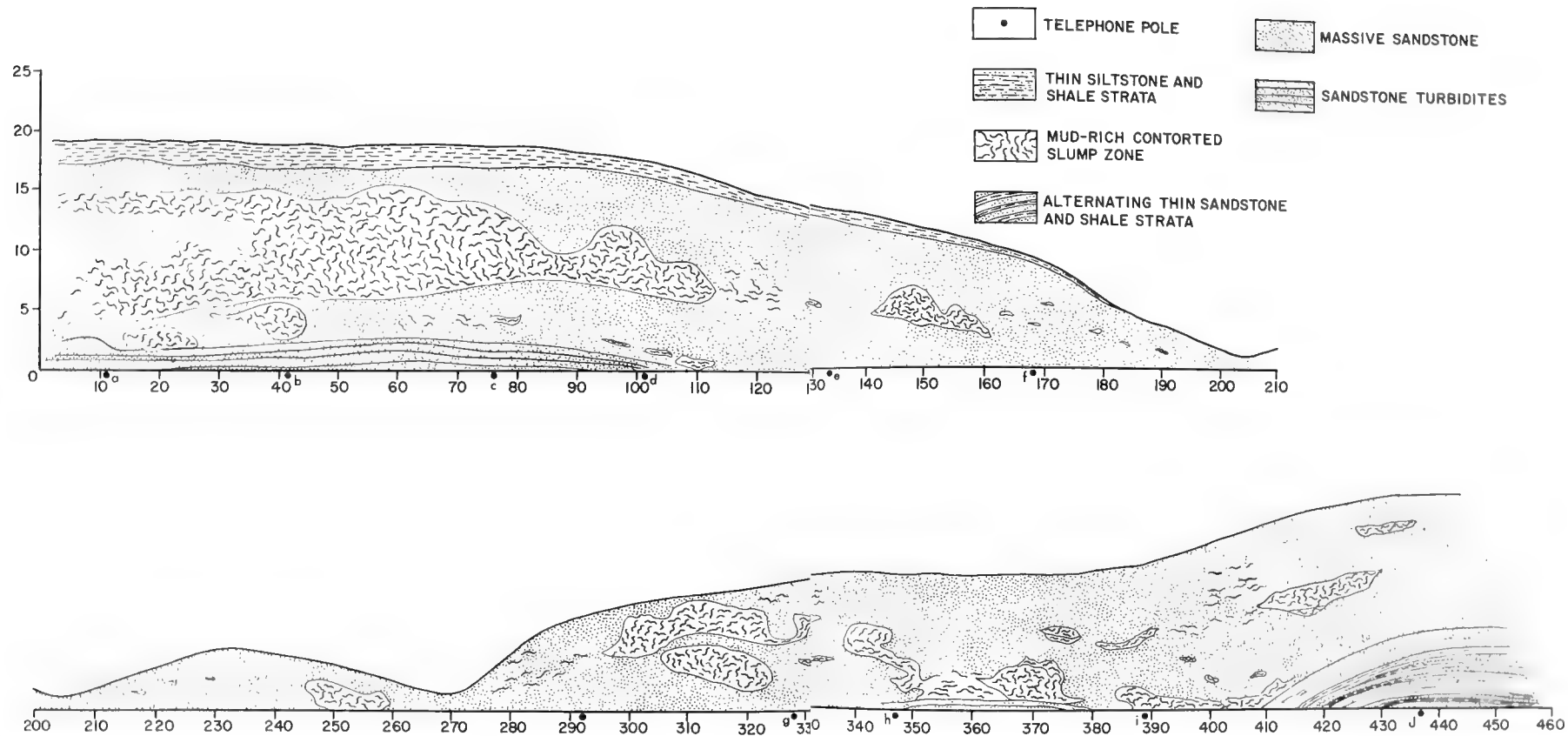


FIGURE 6.—Graphic depiction of Annot Sandstone exposure at Sclos de Contes locality (Figure 5). (Horizontal and vertical scales in meters; $\times 2$ vertical exaggeration.)



FIGURE 7.—Examples of diagnostic canyon margin stratification types (examples selected from Crête de la Barre section): A, type 1 unit (Figure 2, sequence 22); B, type 2 unit (Figure 2, sequence 21); C, type 3 unit (Figure 2, sequence 3); (hammer = 2 cm).

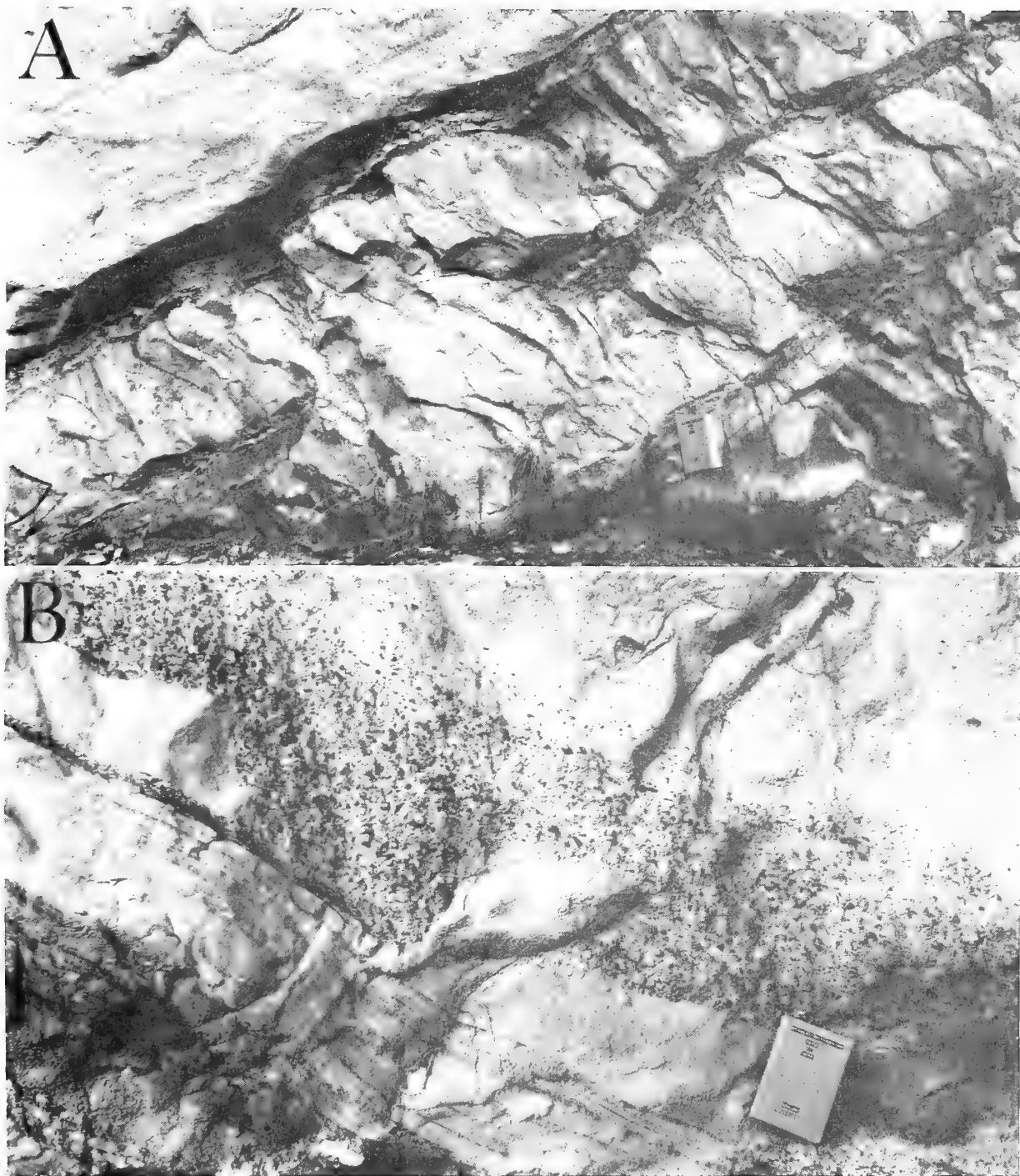


FIGURE 8.—Structures displayed by type 1 massive sandstone units at Menton locality (Figure 1, arrow 4); A, discontinuous and truncated shale horizons; B, cut-and-fill base of a graded pebbly sandstone cuts underlying thin shale and sandstone. (Book length = 20 cm.)

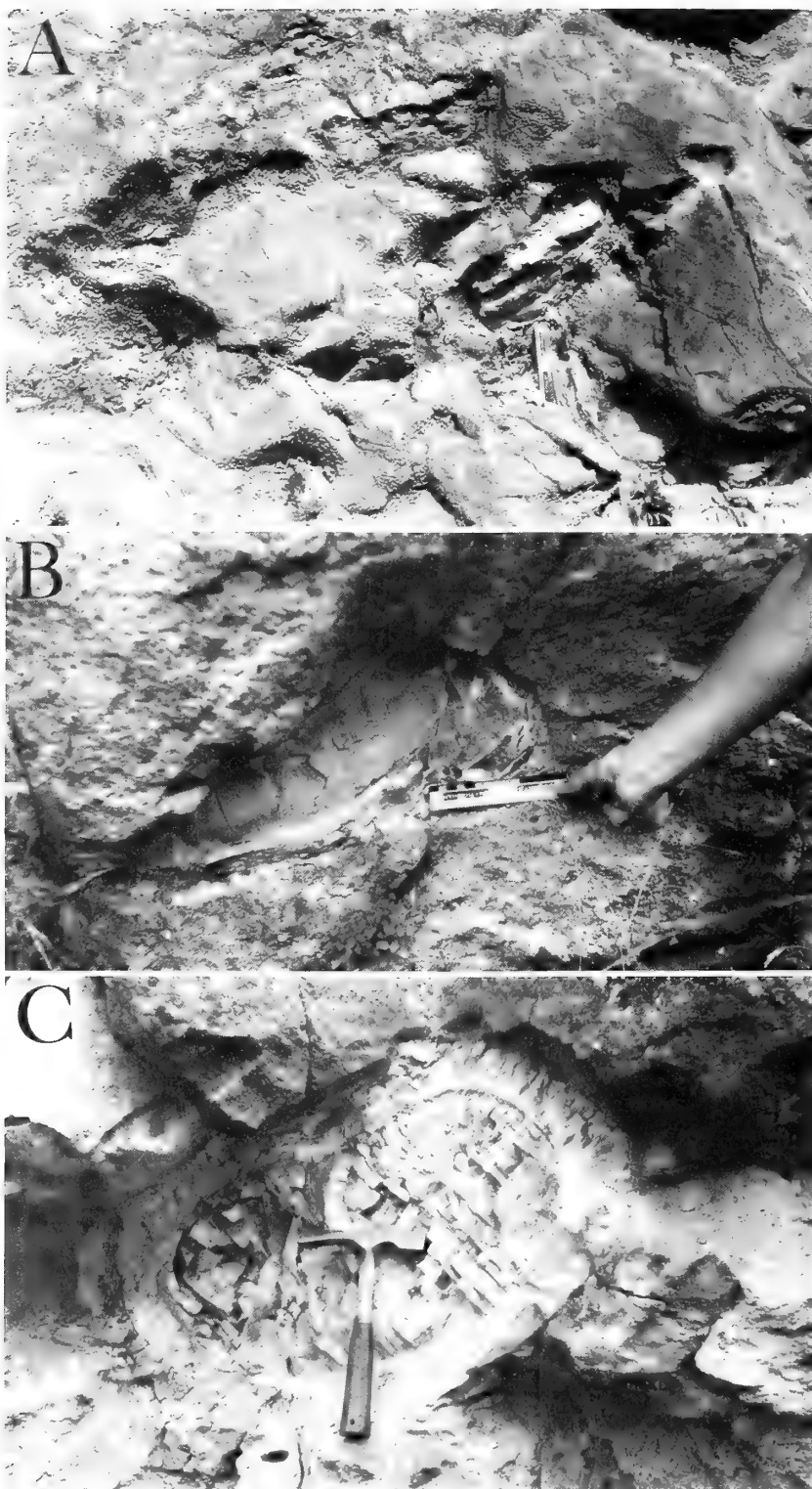


FIGURE 9.—A, shale “rip-up” clasts (Menton); B, sandstone olistolith (Contes); C, armored mudball (Contes) in type 1 sandstone units. (Ruler scale = 15 cm; hammer = 28 cm.)

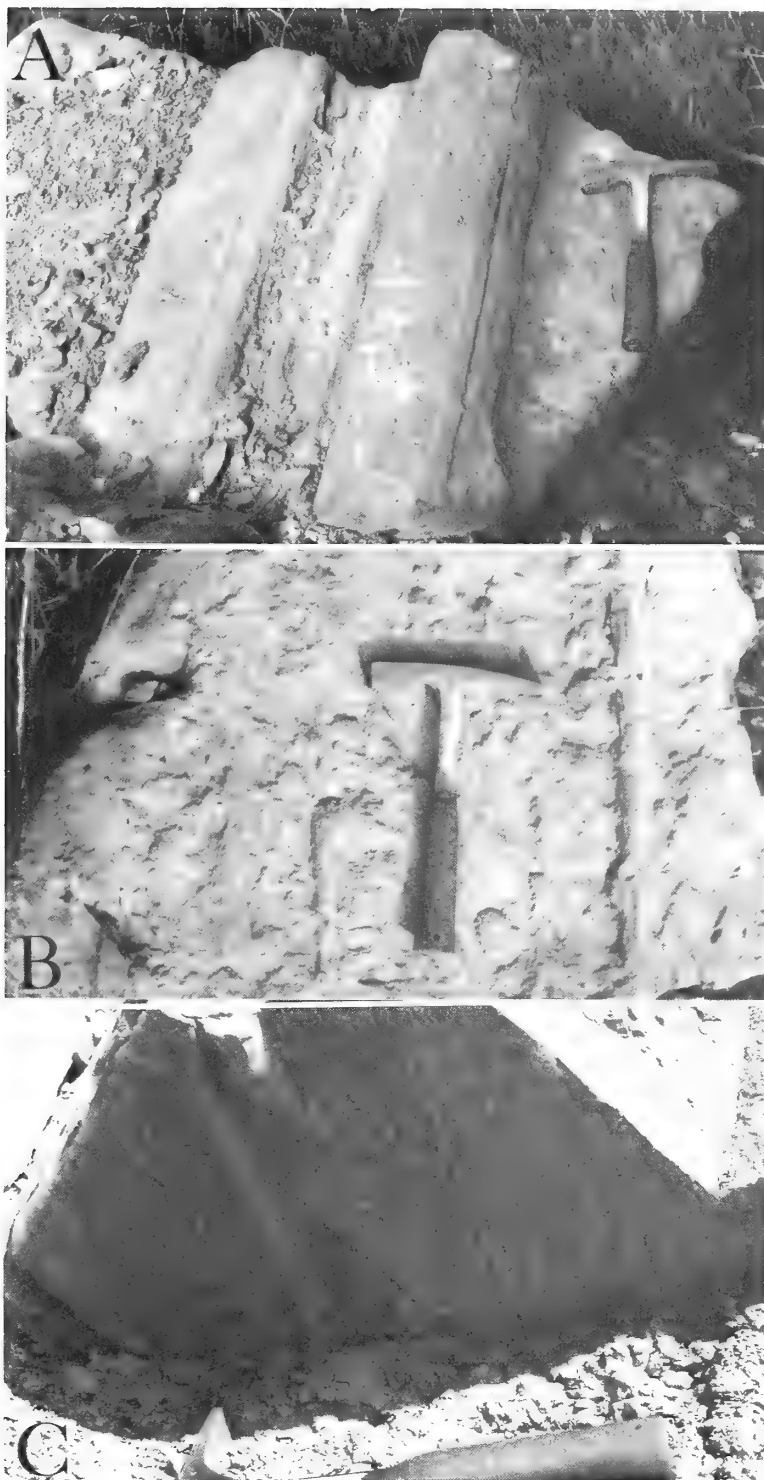


FIGURE 10.—Groove marks on soles of sandstone beds at Crête de la Barre section: A and B, Figure 2, sequence 35; C, diverging marks of sole, Figure 2, sequence 7. (Hammer = 28 cm.)

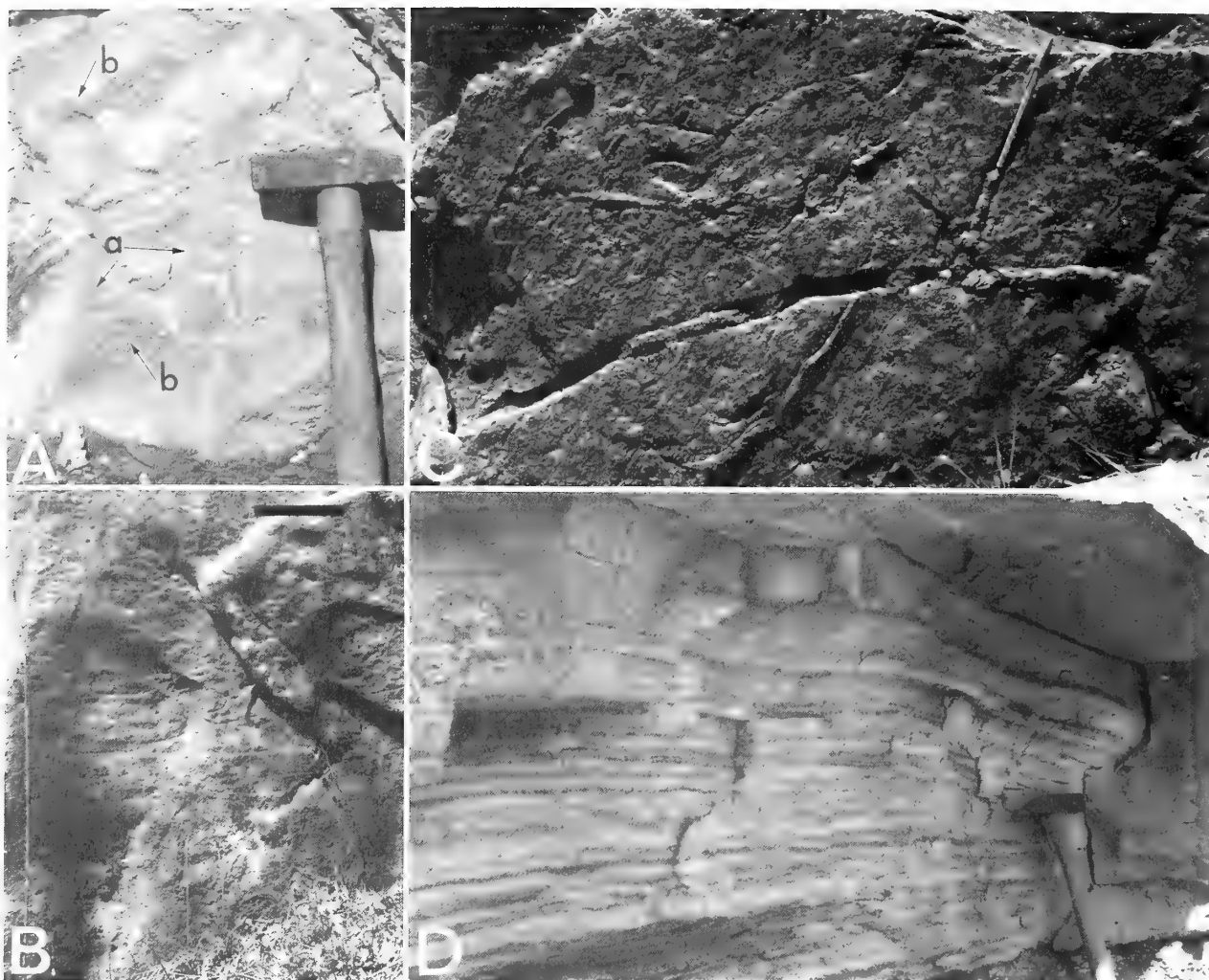


FIGURE 11.—A, Flame structures (a) and convolute lamination (b) at Sclos de Contes locality (Figure 6, near point 430 m); B, dish structures in type 1 massive sandstone bed, near Braux (bar scale = 50 cm); C, bioturbated sandstone surface at Crête de la Barre section (pencil = 15 cm); D, laminations of plant matter and mica (dark layers) in sandstone at Sclos de Contes locality (Figure 6, near point 420 m).

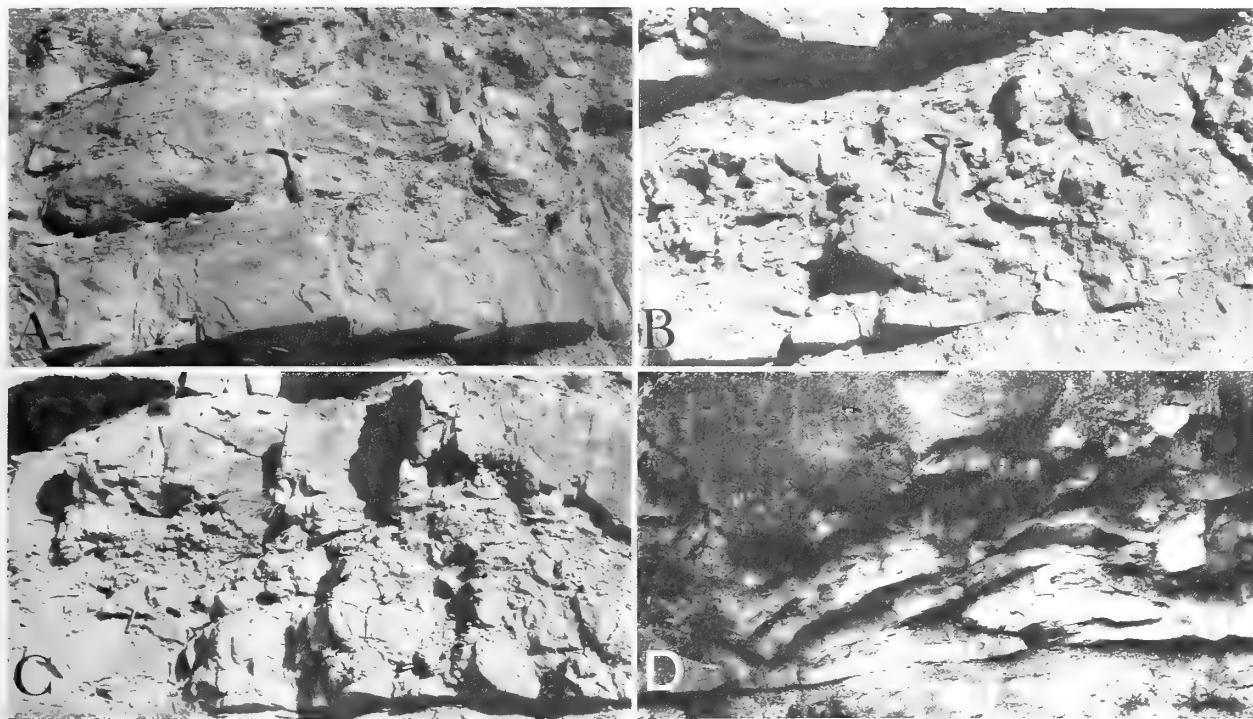


FIGURE 12.—Examples of type 2 stratification: A and B, deformed layers above thin, distinctly stratified sandstone at Crête de la Barre section (Figure 2, sequences 5 and 8); C, deformed layer forming the part of stratum (Figure 2, above sequence 8); D, deformed base of thick unit mapped at Sclos de Contes (Figure 6, near point 370 m); hammer = 28 cm; book = 20 cm.



FIGURE 13.—Examples of type 3 stratification: A, original bedding completely deformed in layer at Crête de la Barre section (Figure 2, sequence 6); B, chaotic units in massive sandstone at Sclos de Contes section in 18-m-thick section, near telephone poles *b* and *c*, Figure 6.



FIGURE 14.—Graded turbidite sequences associated with canyon margin facies: A, T_{a-b} at Menton locality (Figure 1, arrow 4); B, upper units is a T_{b-e} sequence and lower unit is a T_{a-b} bed (Figure 2, exposure between sequences 3 and 4); C, T_{c-e} sequence at Crête de la Barre section (Figure 2, below sequence 2). (Ruler scale = 15 cm; hammer = 28 cm.)

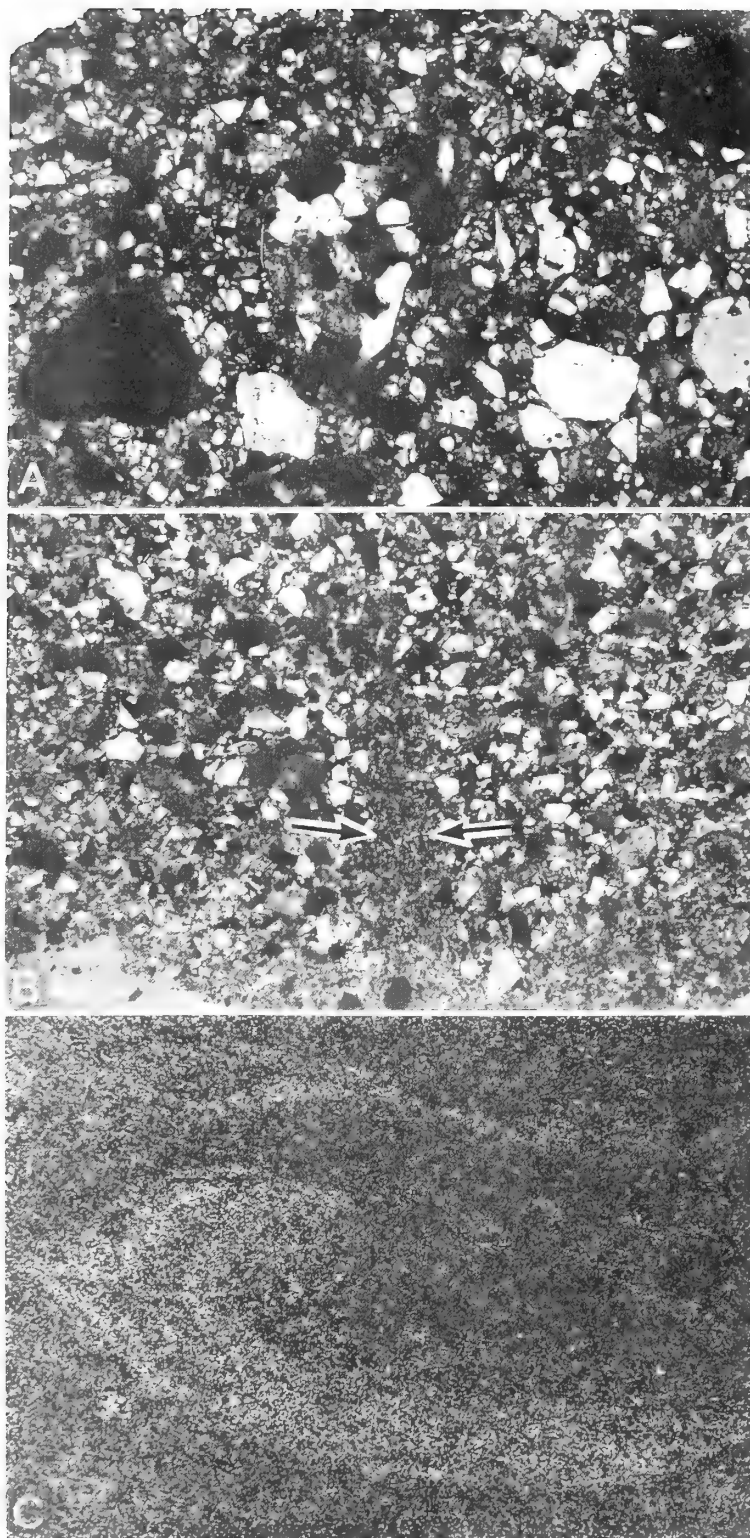


FIGURE 15.—Photomicrographs of selected Annot Sandstone samples: A, coarse, poorly sorted sandstone showing large grains (>2 mm) supported by coarse to medium-grained sand framework grains and a silty mud matrix, from Menton locality (Figure 1, arrow 4); B, thin flame of fine-grained sandstone and siltstone (arrows) injected into medium- to coarse-grained sandstone at Crête de la Barre (Figure 2, sequence 22); C, flowage (dish or water escape) structure in fine-grained sandstone-siltstone section at Crête de la Barre (Figure 2, sequence 3).

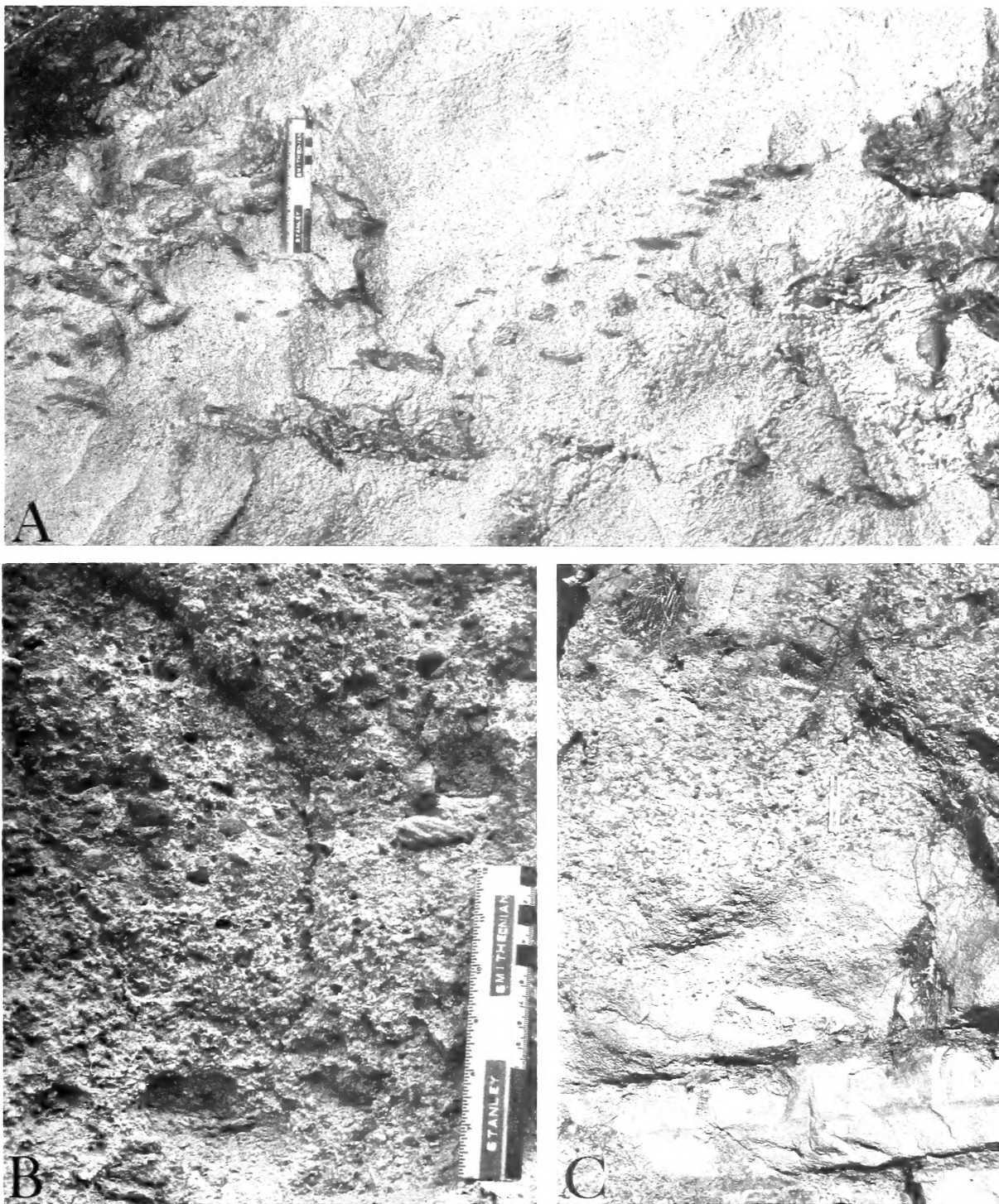


FIGURE 16.—A, Shale clast imbrication in massive type 1 sandstone unit (Menton locality); B, pebble imbrication and reversed graded bedding in type 1 unit (Contes locality); C, small gravely sandstone-filled channel (random pebble orientation) truncating sandstone (Menton locality). (Ruler scale = 15 cm.)

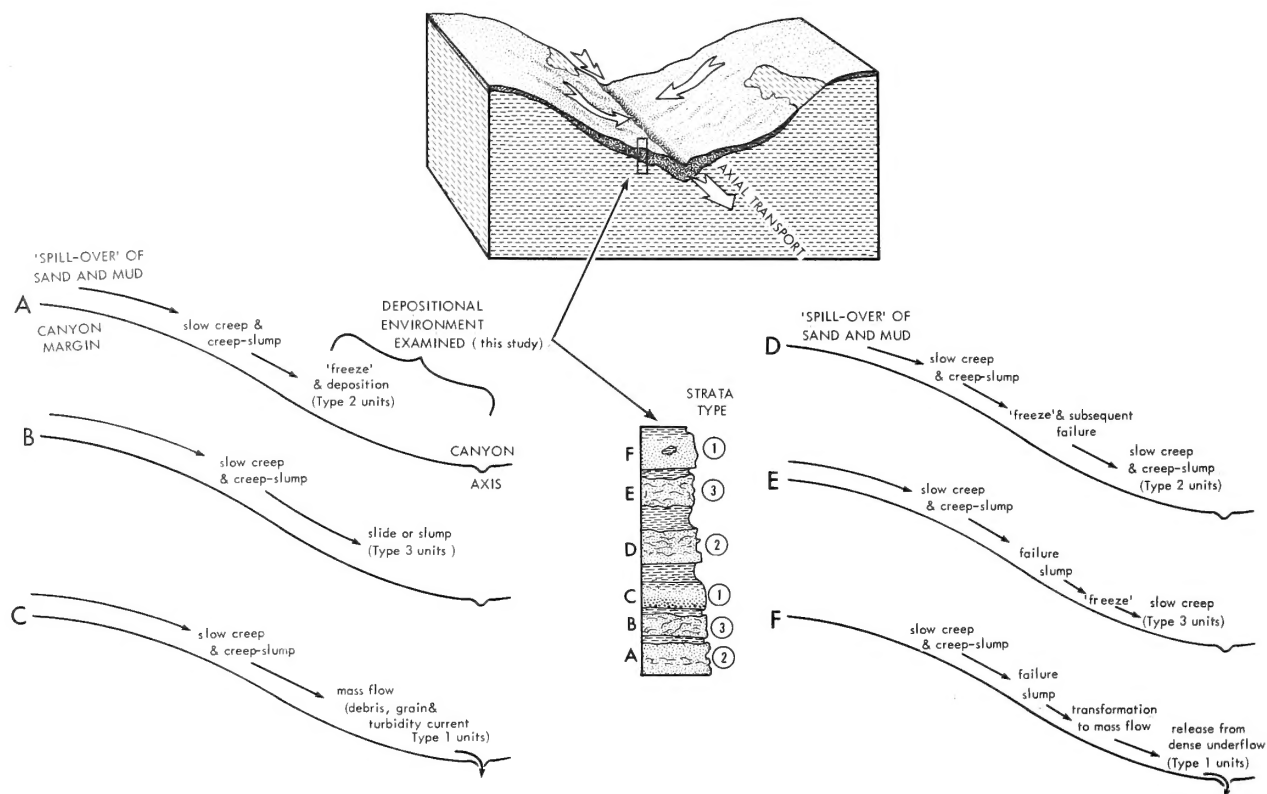


FIGURE 17.—Schematic summarization of canyon margin sedimentation and lateral infill based on study of three Annot Sandstone localities, emphasizing the diagnostic erosion→transport→deposition pattern and variability of successive transformation modes.

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